

Title	BOUNDARY LIMITS OF MONOTONE SOBOLEV FUNCTIONS ON METRIC SPACES
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Citation	Osaka Journal of Mathematics. 58(1) p.135-p.147
Issue Date	2021-01
oaire:version	VoR
URL	<a href="https://doi.org/10.18910/78994">https://doi.org/10.18910/78994</a>
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# BOUNDARY LIMITS OF MONOTONE SOBOLEV FUNCTIONS ON METRIC SPACES

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(Received August 19, 2019, revised September 13, 2019)

## Abstract

In this paper we are concerned with weighted boundary limits of monotone Sobolev functions in Orlicz spaces on bounded  $(\eta, \psi)$ -John domains in a metric space. We also deal with Lindelöf type theorems for monotone Sobolev functions on uniform domains in a metric space.

## 1. Introduction

A continuous function  $u$  on an open set  $\Omega$  in  $\mathbf{R}^n$  is called monotone in the sense of Lebesgue (see [11]) if the equalities

$$\max_{\overline{G}} u = \max_{\partial G} u \quad \text{and} \quad \min_{\overline{G}} u = \min_{\partial G} u$$

hold whenever  $G$  is a domain with compact closure  $\overline{G} \subset \Omega$ . A function  $u \in W_{loc}^{1,p}(\Omega)$  is  $\mathcal{A}$ -harmonic if it is a weak solution of equation

$$\operatorname{div}(\mathcal{A}(x, \nabla u)) = 0,$$

where  $\mathcal{A}(x, \xi) \cdot \xi \approx |\xi|^p$  for some fixed  $p \in (1, \infty)$ ,  $\xi \in \mathbf{R}^n$  (see [9]). Harmonic functions are monotone,  $\mathcal{A}$ -harmonic functions and hence coordinate functions of quasiregular mappings are monotone (see [9] and [28]), and thus the class of monotone functions is considerably wide. If  $u$  is a monotone Sobolev function on  $\Omega$  and  $p > n - 1$ , then

$$(1.1) \quad |u(x) - u(y)| \leq C(n, p) r^{1-n/p} \left( \int_{2B} |\nabla u(z)|^p dz \right)^{1/p}$$

whenever  $y \in B = B(x, r)$  with  $2B \subset \Omega$ , where  $C(n, p)$  is a positive constant depending only on  $n$  and  $p$  (see [9], [22, Chap. 8] and [31, Section 16]). In [6], [13], [14], [15] and [21], boundary behavior of monotone Sobolev functions were studied using the inequality like (1.1). For harmonic functions and polyharmonic functions, see [17, 18, 19, 20, 26, 27]. We refer to [10] for  $\mathcal{A}$ -harmonic functions and [30] for quasiregular mappings.

We consider a positive nondecreasing function  $\varphi$  on the interval  $[0, \infty)$  such that  $\varphi$  is of log-type, that is, there exists a positive constant  $C$  satisfying

$$(1.2) \quad \varphi(r^2) \leq C\varphi(r) \quad \text{for all } r \geq 0.$$

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2020 Mathematics Subject Classification. 31B25, 46E35.

The second author was partially supported by Grant-in-Aid for Scientific Research (C), No. 18K03332, Japan Society for the Promotion of Science.

Set  $\Phi_p(r) = r^p \varphi(r)$  for  $p > 1$ . For properties for functions of log-type, see e.g., [24].

Mizuta [19] studied weighted boundary limits of harmonic functions when  $D$  is a bounded Lipschitz domain in  $\mathbf{R}^n$  and a weight is a nonnegative monotone function on the interval  $(0, \infty)$  satisfying the doubling condition, as an extension of [18]. In fact, he proved the following:

**Theorem A** ([19, Theorem 1]). *Let  $\omega$  be a nonnegative monotone function on the interval  $(0, \infty)$  satisfying the doubling condition, that is, there exists a positive constant  $C$  such that*

$$(1.3) \quad C^{-1}\omega(r) \leq \omega(2r) \leq C\omega(r) \quad \text{for all } r > 0.$$

Set

$$\tilde{\kappa}(r) = \left( \int_r^1 t^{(1-n)/(p-1)} \omega(t)^{-1/(p-1)} (\varphi(t^{-1}))^{-1/(p-1)} dt \right)^{1-1/p}.$$

Suppose  $u$  is a harmonic function in a bounded Lipschitz domain  $D$  in  $\mathbf{R}^n$  and satisfies

$$\int_D \Phi_p(|\nabla u(z)|) \omega(\delta_D(z)) dz < \infty,$$

where  $\delta_D(z) = \text{dist}(z, D^c)$ .

(1) If  $\tilde{\kappa}(0) = \infty$ , then

$$\lim_{x \rightarrow \partial D} \tilde{\kappa}(\delta_D(x))^{-1} u(x) = 0.$$

(2) If  $\tilde{\kappa}(0) < \infty$ , then  $u$  has a finite limit at each boundary point of  $D$ .

For the existence of boundary limits of harmonic functions in the case when  $\Phi_p(r) = r^p$  and  $\omega(r) = r^\alpha$ , see Carleson [2], Mizuta [17] and Wallin [32], etc.

Let  $X$  be a metric space with a metric  $d$  and  $\mu$  be a Borel measure on  $X$  which is positive and finite on balls. We denote by  $B(x, r)$  the open ball centered at  $x \in X$  with radius  $r > 0$  and set  $\lambda B = B(x, \lambda r)$  for each ball  $B = B(x, r)$  and  $\lambda > 0$ . Let  $\mu$  be a Borel measure on  $X$  satisfying the doubling condition:

$$(1.4) \quad \mu(2B) \leq C_\mu \mu(B)$$

for every ball  $B \subset X$ . We further assume that

$$(1.5) \quad \frac{\mu(B(x', r'))}{\mu(B(x, r))} \geq C \left( \frac{r'}{r} \right)^Q$$

for all  $x, x' \in \overline{D}$  with  $x' \in B(x, r)$  and  $0 < r' \leq r$ , where  $Q > 1$ . Here note that if  $\mu$  satisfies (1.4), then (1.5) with  $Q = \log_2 C_\mu$  holds (see e.g. [1, Lemma 3.3] and [8]).

In this paper, we are concerned with boundary limits of functions  $u$  on a domain  $D \subset X$  for which there exists a nonnegative function  $g \in L_{loc}^p(D; \mu)$  such that

$$(1.6) \quad |u(x) - u(x')| \leq Cr \left( \int_{\sigma B} g(z)^p d\mu(z) \right)^{1/p}$$

for every  $x, x' \in B$  with  $\sigma B \subset D$ , where  $\sigma > 1$ ,  $B = B(y, r)$  and

$$(1.7) \quad \int_D \Phi_p(g(z)) \omega(\delta_D(z)) d\mu(z) < \infty,$$

where  $\omega$  is a nonnegative monotone function on  $(0, \infty)$  satisfying (1.3). Here we used the standard notation

$$\int_E u(z) d\mu(z) = \frac{1}{\mu(E)} \int_E u(z) d\mu(z)$$

for a measurable set  $E$  with  $0 < \mu(E) < \infty$ . Note that (1.6) is a stronger property than  $p$ -Poincaré inequality. Also, if the pair of  $u$  and  $g$  satisfies a  $p$ -Poincaré inequality in  $D$  with  $p > Q - 1$  and  $u$  satisfies

$$\sup_{x, x' \in B} |u(x) - u(x')| \leq \sup_{x, x' \in \partial B} |u(x) - u(x')|$$

for each ball  $B$  with  $\sigma B \subset D$ , then the pair of  $u$  and  $g$  satisfies (1.6) (see [8, Section 7]). We refer to [1] and [8, Section 11] for Poincaré inequalities of Carnot group with the Carnot-Carathéodory metric and [3] and [12] for recent studies about Orlicz spaces in a general metric setting.

When  $\Phi_p(r) = r^p$  and  $\omega(r) = r^\alpha$ , the boundary limits of monotone Sobolev functions on bounded John domains in a metric space were studied in [6]. Recently, this result has been extended by the authors [7] to the Orlicz case, that is,  $\Phi_p(r) = r^p \varphi(r)$  and  $\omega(r) = r^\alpha$ . For harmonic functions, polyharmonic functions and monotone functions on the upper half space  $\mathbf{R}_+^n$ , see [18, 20].

Our first aim in this paper is to find a positive function  $k(r)$  such that  $k(\delta_D(x))u(x)$  tends to zero as  $x$  tends to the boundary  $\partial D$  when  $u$  is a function on an  $(\eta, \psi)$ -John domain  $D$  satisfying (1.6) and (1.7) (Theorem 2.1), as an extension of Theorem A (see also [6, 7, 18, 20]). See Section 2 for the definition of  $(\eta, \psi)$ -John domain. The key lemma for our results is Lemma 3.3 below.

On the other hand, using the inequality (1.1), Lindelöf theorems for monotone Sobolev functions on the half space of  $\mathbf{R}^n$  were studied in the  $L^p$  case when  $\omega(r) = r^\alpha$  ([5]), as an extension of Mizuta [21, Theorem 2] and Manfredi-Villamor [14, 15]. This result was extended to a uniform domain in [4].

Our second aim in this paper is to establish Lindelöf theorems when  $u$  is a function on a uniform domain  $D \subset X$  satisfying (1.6) and

$$(1.8) \quad \int_D g(z)^p \omega(\delta_D(z)) d\mu(z) < \infty$$

(Theorem 5.1), as an extension of [4, 5, 14, 21] (see Section 5 for the definition of uniform domain). We discuss the size of the exceptional set in Theorem 5.1 (Remark 5.2).

Throughout this paper, let  $C$  denote various constants independent of the variables in question.

## 2. Weighted boundary limits

Let  $\eta$  be a strictly increasing continuous function on  $[0, \infty)$  such that  $\eta(0) = 0$ ,

$$(2.1) \quad \eta(2t) \leq c_1 \eta(t) \quad \text{for all } t > 0$$

with a constant  $c_1 \geq 1$ ,

$$(2.2) \quad \limsup_{t \rightarrow 0} t^{-1} \eta(t) < \infty$$

and

$$(2.3) \quad \int_0^1 t^{-\varepsilon-1} \eta^{-1}(t) dt < \infty$$

for some small  $\varepsilon$ . We say that a domain  $D$  in  $X$  is John with respect to  $\eta$  (simply  $\eta$ -John) if there is a point  $x^* \in D$  such that each  $x \in D$  can be joined to  $x^*$  by a rectifiable curve  $\gamma$  satisfying

$$(2.4) \quad \delta_D(z) \geq \eta(\ell(\gamma(x, z))) \quad \text{for all } z \in \gamma,$$

where  $\gamma(x, z)$  and  $\ell(\gamma(x, z))$  denote the subarc of  $\gamma$  connecting  $x$  and  $z$  and the length of  $\gamma(x, z)$ , respectively. We refer  $x^*$  to the John center. If  $\eta(t) = c_J t^s$  with  $s \geq 1$  and a positive constant  $c_J$ , then an  $\eta$ -John domain is called  $s$ -John. Further, we consider a positive nondecreasing function  $\psi$  on  $(0, \infty)$  such that  $\psi(0) = \lim_{r \rightarrow 0} \psi(r) = 0$ . We say that a domain  $D$  is  $(\eta, \psi)$ -John if each  $x \in D$  can be joined to  $x^*$  by a rectifiable curve  $\gamma$  satisfying (2.4) and

$$(2.5) \quad \delta_D(z) \geq \psi(\delta_D(x)) \quad \text{for all } z \in \gamma.$$

Here note that every  $\eta$ -John domain is  $(\eta, \psi)$ -John domain if we take  $\psi(t) = \min\{\eta(t/2), t/2\}$  (see [6, Example 1.5]). See also [16] for some examples of  $\eta$ -John domains.

Consider the function

$$\kappa(r_1, r_2) = \left( \int_{r_1}^{r_2} t^{(1-Q)/(p-1)-1} \omega(t)^{-1/(p-1)} (\varphi(t^{-1}))^{-1/(p-1)} \eta^{-1}(t) dt \right)^{1-1/p}$$

for  $0 \leq r_1 < r_2 < \infty$ ; set  $\kappa(r) = \kappa(r, 1)$  for  $0 \leq r < 1$ .

Our first result is the following theorem, which gives an extension of Theorem A (see also [6, 7, 18, 20]).

**Theorem 2.1.** *Let  $D$  be a bounded  $(\eta, \psi)$ -John domain in  $X$  such that  $\partial D \neq \emptyset$ . Assume that the pair of  $u$  and  $g$  satisfies (1.6) and (1.7).*

(1) *If  $\kappa(0) = \infty$ , then*

$$\lim_{\delta_D(x) \rightarrow 0} \kappa(\psi(\delta_D(x)))^{-1} u(x) = 0.$$

(2) *If  $\kappa(0) < \infty$ , then  $u$  is bounded on  $D$ .*

For the best possibility of Theorem 2.1 (1) as to the order of infinity, we refer to [19, Proposition 4] for harmonic functions.

**REMARK 2.2.** Let  $D$  be a bounded  $s$ -John domain in  $X$ ,  $s \geq 1$ , that is,  $D$  is  $\eta$ -John with  $\eta(t) = c_J t^s$  and a positive constant  $c_J$ . Then we see that  $D$  is an  $(\eta, c_2 \eta)$ -John domain with  $c_2 = \min\{2^{-s}, (2c_J)^{-1}(\text{diam} D)^{1-s}\}$ . For the result from Theorem 2.1 in the case when  $D$  is a bounded  $s$ -John domain, see [7, Corollaries 4.1 and 4.2].

**REMARK 2.3.** For  $s \geq 1$ , let

$$G_s = \{x = (x', x_n) \in \mathbf{R}^{n-1} \times \mathbf{R} : |x'| < 1, 0 < x_n < 2, |x'| < x_n^s\}.$$

Then we see that  $G_s$  is an  $(\eta, \psi)$ -John domain with  $\eta(t) = c_3 t^s$  and  $\psi(t) = t$ , where  $c_3$  is a positive constant. In fact, for  $x = (x', x_n) \in G_s$  and  $0 < x_n < 1$ , we define a rectifiable curve  $\gamma$  joining  $x$  and  $x^* = (0, \dots, 0, 3/2)$  by

$$\gamma(t) = \begin{cases} ((1-t)x', x_n) & \text{if } 0 \leq t \leq 1, \\ (0, \dots, 0, tx_n) & \text{if } 1 < t \leq 3/(2x_n). \end{cases}$$

Then  $\gamma$  satisfies (2.4) and (2.5) since  $\delta_{G_s}(z)$  is comparable to  $z_n^s - |z'|$  when  $z = (z', z_n) \in G_s$  and  $0 < z_n < 1$ .

For the result from Theorem 2.1 in the case when  $D = G_s$ , see [7, Corollary 4.3].

### 3. Lemmas

For proofs of Theorems 2.1 and 5.1, we prepare some lemmas. Using (1.2), we have the following.

**Lemma 3.1** (cf. [7, Lemma 2.2] and [23, Theorem 3]). *Let  $u$  and  $g$  be functions on  $D$  satisfying (1.6). Suppose  $0 < \varepsilon < 1$ . Then*

$$(3.1) \quad |u(x) - u(y)| \leq C\delta_D(x)(\varphi(\delta_D(x)^{-1}))^{-1/p} \left( \int_{\sigma B(x)} \Phi_p(g(z)) d\mu(z) \right)^{1/p} + C\delta_D(x)^{1-\varepsilon},$$

whenever  $x \in D$  and  $y \in B(x)$ , where  $B(x) = B(x, \delta_D(x)/(2\sigma))$  and  $C$  may depend on  $\varepsilon$ .

**Lemma 3.2** ([6, Lemma 2.2]). *Let  $\sigma > 1$  and  $\mu$  be a Borel measure on  $X$  satisfying the doubling condition (1.4). Suppose  $x$  and  $y$  can be joined by a rectifiable curve  $\gamma$  in a domain  $D$  satisfying (2.4). Then there exists a finite chain of balls  $B_0, B_1, \dots, B_N$  ( $N$  may depend on  $\gamma$ ) with the following properties:*

- (i)  $B_j = B(z_j, \delta_D(z_j)/(2\sigma))$  with  $z_j \in \gamma$ ,  $z_0 = x$  and  $y \in B_N$ ;
- (ii)  $B_j \cap B_{j+1} \neq \emptyset$  for all  $0 \leq j \leq N-1$ ;
- (iii) For each  $t > 0$ , the number of  $z_j$  such that  $t/2 < \delta_D(z_j) \leq t$  is less than  $c_4\eta^{-1}(t)/t$ , where  $c_4$  is a positive constant depending only on  $\sigma$ ;
- (iv)  $\sum_{j=0}^N \chi_{\sigma B_j} \leq c_5$ , where  $c_5$  is a positive constant depending only on  $\sigma$  and  $C_\mu$ .

**Lemma 3.3.** *Let  $u$  and  $g$  be functions on  $D$  satisfying (1.6). Let  $B$  be an open ball with radius  $R$ . Then*

$$(3.2) \quad |u(x) - u(y)| \leq C\kappa(\psi(\delta_D(x)), d_\gamma) \left( \frac{R^Q}{\mu(B)} \int_{E_\gamma} \Phi_p(g(w)) \omega(\delta_D(w)) d\mu(w) \right)^{1/p} + C \int_0^{d_\gamma} t^{-\varepsilon-1} \eta^{-1}(t) dt$$

whenever  $x$  and  $y$  can be joined by a rectifiable curve  $\gamma$  in  $D$  satisfying (2.4), (2.5) and  $z \in B$ ,  $\delta_D(z) < R$  for all  $z \in \gamma$ , where  $E_\gamma = \cup_{z \in \gamma} \sigma B(z)$  and  $d_\gamma = 4 \max_{z \in \gamma} \delta_D(z)$ .

**Proof.** Take a finite chain of balls  $B_0, B_1, \dots, B_N$  with  $B_j = B(z_j)$  as in Lemma 3.2. Pick  $x_j \in B(z_{j-1}) \cap B(z_j)$  for  $1 \leq j \leq N$ ; set  $x_0 = x$  and  $x_{N+1} = y$ . By (3.1), (1.3) and (1.5), we see that

$$\begin{aligned} & |u(x_j) - u(x_{j+1})| \\ & \leq C\delta_D(z_j)\omega(\delta_D(z_j))^{-1/p}(\varphi(\delta_D(z_j)^{-1}))^{-1/p}\mu(\sigma B_j)^{-1/p} \\ & \quad \times \left( \int_{\sigma B_j} \Phi_p(g(w))\omega(\delta_D(w))d\mu(w) \right)^{1/p} + C\delta_D(z_j)^{1-\varepsilon} \end{aligned}$$

$$\begin{aligned} &\leq C\delta_D(z_j)\omega(\delta_D(z_j))^{-1/p}(\varphi(\delta_D(z_j)^{-1}))^{-1/p}(\delta_D(z_j)/R)^{-Q/p}\mu(B)^{-1/p} \\ &\quad \times \left( \int_{\sigma B_j} \Phi_p(g(w))\omega(\delta_D(w))d\mu(w) \right)^{1/p} + C\delta_D(z_j)^{1-\varepsilon} \end{aligned}$$

for  $0 \leq j \leq N$ . Then we have by Hölder's inequality and Lemma 3.2 (iv)

$$\begin{aligned} &|u(x) - u(y)| \\ &\leq |u(x_0) - u(x_1)| + |u(x_1) - u(x_2)| + \cdots + |u(x_N) - u(x_{N+1})| \\ &\leq C \left( \frac{R^Q}{\mu(B)} \right)^{1/p} \left( \sum_{j=0}^N \delta_D(z_j)^{(p-Q)/(p-1)} \omega(\delta_D(z_j))^{-1/(p-1)} (\varphi(\delta_D(z_j)^{-1}))^{-1/(p-1)} \right)^{(p-1)/p} \\ &\quad \times \left( \int_{E_\gamma} \Phi_p(g(w))\omega(\delta_D(w)) d\mu(w) \right)^{1/p} + C \sum_{j=0}^N \delta_D(z_j)^{1-\varepsilon}. \end{aligned}$$

Hence it suffices to show that

$$(3.3) \quad \sum_{j=0}^N \delta_D(z_j)^{(p-Q)/(p-1)} \omega(\delta_D(z_j))^{-1/(p-1)} (\varphi(\delta_D(z_j)^{-1}))^{-1/(p-1)} \leq C\kappa(\psi(\delta_D(x)), d_\gamma)^{p/(p-1)}$$

and

$$(3.4) \quad \sum_{j=0}^N \delta_D(z_j)^{1-\varepsilon} \leq C \int_0^{d_\gamma} t^{-\varepsilon-1} \eta^{-1}(t) dt.$$

For this purpose, take natural numbers  $k_0$  and  $k_1$  such that  $2^{-k_0+1} < d_\gamma \leq 2^{-k_0+2}$  and  $2^{-k_1-1} < \psi(\delta_D(x)) \leq 2^{-k_1}$ . Then we see from Lemma 3.2 (iii) that

$$\begin{aligned} &\sum_{j=0}^N \delta_D(z_j)^{(p-Q)/(p-1)} \omega(\delta_D(z_j))^{-1/(p-1)} (\varphi(\delta_D(z_j)^{-1}))^{-1/(p-1)} \\ &= \sum_{k=k_0}^{k_1} \left( \sum_{2^{-k-1} < \delta_D(z_j) \leq 2^{-k}} \delta_D(z_j)^{(p-Q)/(p-1)} \omega(\delta_D(z_j))^{-1/(p-1)} (\varphi(\delta_D(z_j)^{-1}))^{-1/(p-1)} \right) \\ &\leq C \sum_{k=k_0}^{k_1} 2^{-k\{(p-Q)/(p-1)-1\}} \omega(2^{-k})^{-1/(p-1)} (\varphi((2^{-k})^{-1}))^{-1/(p-1)} \eta^{-1}(2^{-k}) \\ &\leq C \int_{2^{-k_1}}^{2^{-k_0+1}} t^{(1-Q)/(p-1)-1} \omega(t)^{-1/(p-1)} (\varphi(t^{-1}))^{-1/(p-1)} \eta^{-1}(t) dt \\ &\leq C \int_{\psi(\delta_D(x))}^{d_\gamma} t^{(1-Q)/(p-1)-1} \omega(t)^{-1/(p-1)} (\varphi(t^{-1}))^{-1/(p-1)} \eta^{-1}(t) dt. \end{aligned}$$

Thus (3.3) is obtained. Further, we see that

$$\begin{aligned} \sum_{j=0}^N \delta_D(z_j)^{1-\varepsilon} &= \sum_{k=k_0}^{k_1} \left( \sum_{2^{-k-1} < \delta_D(z_j) \leq 2^{-k}} \delta_D(z_j)^{1-\varepsilon} \right) \\ &\leq C \sum_{k=k_0}^{k_1} 2^{-k\{(1-\varepsilon)-1\}} \eta^{-1}(2^{-k}) \end{aligned}$$

$$\begin{aligned}
&\leq C \int_{2^{-k_1}}^{2^{-k_0+1}} t^{-\varepsilon-1} \eta^{-1}(t) dt \\
&\leq C \int_0^{d_\gamma} t^{-\varepsilon-1} \eta^{-1}(t) dt.
\end{aligned}$$

Thus (3.4) is obtained and the proof is completed.  $\square$

#### 4. Proof of Theorem 2.1

Proof of Theorem 2.1. Fix  $r > 0$  such that  $r < \min\{\delta_D(x^*), 1/4\}$ . For  $x \in F(r) = \{z \in D : \delta_D(z) < r\}$ , take a curve  $\gamma$  joining  $x$  to the John center  $x^*$  and satisfying (2.4) and (2.5). We can find  $y \in \gamma$  such that  $\delta_D(y) = r$  and  $\delta_D(z) \leq r$  for all  $z \in \gamma(x, y)$ . Since  $E_{\gamma(x,y)} \subset F(2r)$  and  $d_{\gamma(x,y)} \leq 1$ , using Lemma 3.3 with  $B = B(x^*, \text{diam}D)$ , we have

$$\begin{aligned}
(4.1) \quad |u(x) - u(y)| &\leq C\kappa(\psi(\delta_D(x))) \left( \int_{F(2r)} \Phi_p(g(w)) \omega(\delta_D(w)) d\mu(w) \right)^{1/p} \\
&\quad + C \int_0^1 t^{-\varepsilon-1} \eta^{-1}(t) dt.
\end{aligned}$$

Further, take a path  $\gamma_1$  in  $D$  joining  $y$  and  $x^*$  satisfying (2.4) and (2.5). Hence it follows from Lemma 3.3 with  $B = B(x^*, \text{diam}D)$  that

$$|u(y) - u(x^*)| \leq C\kappa(\psi(r), d_{\gamma_1}) \left( \int_D \Phi_p(g(w)) \omega(\delta_D(w)) d\mu(w) \right)^{1/p} + C \int_0^{d_{\gamma_1}} t^{-\varepsilon-1} \eta^{-1}(t) dt,$$

which implies that  $\sup\{|u(y)| : \delta_D(y) = r\}$  is finite for all  $r > 0$ . If  $\kappa(0) = \infty$ , then it follows from (4.1) and (2.3) that

$$\limsup_{\delta_D(x) \rightarrow 0} \kappa(\psi(\delta_D(x)))^{-1} |u(x)| \leq C \left( \int_{F(2r)} \Phi_p(g(w)) \omega(\delta_D(w)) d\mu(w) \right)^{1/p}.$$

By (1.7), the left hand side is equal to zero.

On the other hand, the case  $\kappa(0) < \infty$  follows readily from Lemma 3.3. Thus our theorem is proved.  $\square$

REMARK 4.1. In the case of (2) in Theorem 2.1, that is,  $\kappa(0) < \infty$ , if we impose a strong condition on  $D$  like locally uniformity, then  $u$  will be seen to have a finite limit at each  $\xi \in \partial D$ . For example, we may consider a condition on  $D$  such that for each  $\xi \in \partial D$ , there exists a positive constant  $c_6$  with the following property: for every  $r > 0$ , there exists a point  $x^*(r)$  such that each  $x \in D \cap B(\xi, r)$  can be joined to  $x^*(r)$  by a path  $\gamma$  in  $D \cap B(\xi, c_6 r)$  satisfying (2.4).

In fact, it follows from Lemma 3.3 that

$$|u(x) - u(y)| \leq C\kappa(0, 4c_6 r) \left( \int_D \Phi_p(g(w)) \omega(\delta_D(w)) d\mu(w) \right)^{1/p} + C \int_0^{4c_6 r} t^{-\varepsilon-1} \eta^{-1}(t) dt$$

for each  $x, y \in D \cap B(\xi, r)$ . Since  $\kappa(0) < \infty$ , this implies that  $u$  has a finite limit at  $\xi$ .

By Theorem 2.1 and Remark 4.1, we obtain the following corollary, which extends The-



orem A. Note here that when  $D$  is a bounded Lipschitz domain in  $X$ ,  $D$  is a bounded  $(\eta, \psi)$ -John domain with  $\eta(t) = ct$  and  $\psi(t) = c't$ .

**Corollary 4.2.** *Let  $D$  be a bounded Lipschitz domain in  $X$  such that  $\partial D \neq \emptyset$ . Set*

$$\kappa(r_1, r_2) = \left( \int_{r_1}^{r_2} t^{(1-Q)/(p-1)} \omega(t)^{-1/(p-1)} (\varphi(t^{-1}))^{-1/(p-1)} dt \right)^{1-1/p}$$

for  $0 \leq r_1 < r_2 < \infty$ ; set  $\kappa(r) = \kappa(r, 1)$  for  $0 \leq r < 1$ . Assume that the pair of  $u$  and  $g$  satisfies (1.6) and (1.7).

(1) If  $\kappa(0) = \infty$ , then

$$\lim_{\delta_D(x) \rightarrow 0} \kappa(\delta_D(x))^{-1} u(x) = 0.$$

(2) If  $\kappa(0) < \infty$ , then  $u$  has a finite limit at each boundary point of  $D$ .

## 5. Lindelöf theorem

In this section, we are concerned with Lindelöf theorems when  $u$  is a function on a uniform domain  $D$  satisfying (1.6) and (1.8), as an extension of [4, 5, 14, 21].

Let  $D$  in  $X$  with  $\partial D \neq \emptyset$  be a uniform domain, that is, there exist positive constants  $A_1$  and  $A_2$  such that each pair of points  $x, y \in D$  can be joined by a rectifiable curve  $\gamma$  in  $D$  for which

$$(5.1) \quad \ell(\gamma) \leq A_1 d(x, y)$$

and

$$(5.2) \quad \delta_D(z) \geq A_2 \min\{\ell(\gamma(x, z)), \ell(\gamma(y, z))\} \quad \text{for all } z \in \gamma$$

(see [29]). For  $\xi \in \partial D$  and  $c > 1$ , set

$$T(\xi; c) = \{x \in D : d(x, \xi) < c\delta_D(x)\}.$$

A function  $u$  defined on  $D$  is said to have a nontangential limit  $L$  at  $\xi \in \partial D$  if

$$\lim_{T(\xi; c) \ni x \rightarrow \xi} u(x) = L$$

for every  $c > 0$ . For each  $\tau \in \mathbf{R}$ , set

$$\kappa_\tau(r_1, r_2) = \left( \int_{r_1}^{r_2} t^{(p-Q+\tau)/(p-1)} \omega(t)^{-1/(p-1)} t^{-1} dt \right)^{1-1/p}$$

and

$$\hat{\kappa}(r_1, r_2) = \left( \int_{r_1}^{r_2} t^{(1-Q)/(p-1)-1} \omega(t)^{-1/(p-1)} \eta^{-1}(t) dt \right)^{1-1/p}$$

for  $0 \leq r_1 < r_2 < \infty$ . Here note that  $\hat{\kappa}(r_1, r_2) = c^{-1+1/p} \kappa_0(r_1, r_2)$  when  $\eta(t) = ct$ .

**Theorem 5.1.** *Let  $u$  be a function on a uniform domain  $D$  with  $g \geq 0$  satisfying (1.6) and (1.8). Suppose that there exists a constant  $\tau \in (0, 1)$  such that  $\kappa_\tau(0, 1) < \infty$ . Set*

$$E = \left\{ \xi \in \partial D : \limsup_{r \rightarrow 0} \frac{r^{Q-\tau} \kappa_\tau(0, r)^p}{\mu(B(\xi, r))} \int_{B(\xi, r) \cap D} g(w)^p \omega(\delta_D(w)) d\mu(w) > 0 \right\}.$$

If  $\xi \in \partial D \setminus E$  and there exists a rectifiable curve  $\gamma$  in  $D$  tending to  $\xi$  along which  $u$  has a finite limit  $L$ , then  $u$  has a nontangential limit  $L$  at  $\xi$ .

REMARK 5.2. Let  $h(r; x) = r^{\tau-Q} \kappa_\tau(0, r)^{-p} \mu(B(x, r))$  for  $x \in \partial D$  and  $r > 0$ . If  $\liminf_{r \rightarrow 0} h(r; x_0) = 0$  for some  $x_0 \in X$ , then  $\mathcal{H}_h(E) = 0$  where  $\mathcal{H}_h$  is the generalized Hausdorff measure with respect to  $h$ , that is, for  $F \subset X$  and  $r_0 > 0$ ,

$$\mathcal{H}_h^{(r_0)}(F) = \inf \left\{ \sum_j h(r_j; x_j); F \subset \bigcup_j B(x_j, r_j), 0 < r_j \leq r_0 \right\}$$

and

$$\mathcal{H}_h(F) = \lim_{r_0 \rightarrow +0} \mathcal{H}_h^{(r_0)}(F).$$

For a proof of Theorem 5.1, we need the following lemmas.

**Lemma 5.3** (cf. [4, Lemma 1]). *Let  $D$  be a uniform domain. Then for each  $\xi \in \partial D$  there exists a rectifiable curve  $\gamma_\xi$  in  $D$  ending at  $\xi$  such that*

$$(5.3) \quad \delta_D(z) \geq A_3 \ell(\gamma_\xi(\xi, z))$$

for all  $z \in \gamma_\xi$ , where  $A_3$  is a constant depending only on  $A_1$  and  $A_2$ .

We use the following lemma which is proved as in Lemma 3.3.

**Lemma 5.4.** *Let  $u$  and  $g$  be functions on  $D$  satisfying (1.6). Let  $B$  be an open ball with radius  $R$ . Then*

$$(5.4) \quad |u(x) - u(y)| \leq C \hat{\kappa}(\psi(\delta_D(x)), d_\gamma) \left( \frac{R^Q}{\mu(B)} \int_{E_\gamma} g(w)^p \omega(\delta_D(w)) d\mu(w) \right)^{1/p}$$

whenever  $x$  and  $y$  can be joined by a rectifiable curve  $\gamma$  in  $D$  satisfying (2.4), (2.5) and  $z \in B$ ,  $\delta_D(z) < R$  for all  $z \in \gamma$ , where  $E_\gamma = \bigcup_{z \in \gamma} \sigma B(z)$  and  $d_\gamma = 4 \max_{z \in \gamma} \delta_D(z)$ .

**Lemma 5.5** (cf. [4, Lemma 3]). *Let  $u$  be a function on a uniform domain  $D$  with  $g \geq 0$  satisfying (1.6) and (1.8). Set*

$$\tilde{E} = \left\{ \xi \in \partial D : \limsup_{r \rightarrow 0} \frac{r^p \omega(r)^{-1}}{\mu(B(\xi, r))} \int_{B(\xi, r) \cap D} g(w)^p \omega(\delta_D(w)) d\mu(w) > 0 \right\}.$$

Supposes  $\xi \in \partial D \setminus \tilde{E}$  and there exists a sequence  $\{y_j\}$  such that  $y_j \in \gamma_\xi$ ,  $2^{-j-1} \leq d(\xi, y_j) \leq 2^{-j}$  and  $u(y_j)$  has a finite limit  $L$ , where  $\gamma_\xi$  is as in Lemma 5.3. Then  $u$  has a nontangential limit  $L$  at  $\xi$ .

REMARK 5.6. Since  $r^{Q-\tau} \kappa_\tau(0, r)^p \geq r^{Q-\tau} \kappa_\tau(r/2, r)^p \geq Cr^p \omega(r)^{-1}$ , we see that  $\tilde{E} \subset E$ . When  $\omega(t) = t^\alpha$  and  $p > Q + \alpha - 1$ , we take  $\tau$  such that  $\max\{-p + Q + \alpha, 0\} < \tau < 1$ . Then we have  $\kappa_\tau(0, 1) < \infty$  and

$$r^{Q-\tau} \kappa_\tau(0, r)^p = r^{Q-\tau} \left( \int_0^r t^{(p-Q-\alpha+\tau)/(p-1)} t^{-1} dt \right)^{p-1} \leq Cr^{p-\alpha}.$$

Hence, we see that  $\tilde{E} = E$ . In view of Theorem 5.1, we obtain [4, Theorem 1].

Proof of Lemma 5.5. Fix  $x \in T(\xi; c)$  with  $2^{-j-1} \leq d(\xi, x) \leq 2^{-j}$ . Let  $\gamma$  be a rectifiable curve in  $D$  joining  $x$  and  $y_j$  satisfying (5.1) and (5.2). Take  $y \in \gamma$  such that  $\ell(\gamma(x, y)) = \ell(\gamma(y_j, y))$ , and set  $\gamma_1 = \gamma(x, y)$  and  $\gamma_2 = \gamma(y_j, y)$ . Then  $\gamma_i$  satisfies (2.4) and (2.5) with  $\eta(t) = A_2 t$  and  $\psi(t) = \min\{A_2, 1\}t/2$ . We note that for  $z \in \gamma$

$$(5.5) \quad \delta_D(z) \leq d(\xi, z) \leq d(\xi, x) + d(x, z) \leq (A_1 + 1)d(\xi, x) + A_1 d(\xi, y_j)$$

since we have by (5.1)

$$d(x, z) \leq \ell(\gamma) \leq A_1 d(x, y_j) \leq A_1 (d(\xi, x) + d(\xi, y_j)).$$

Then we have  $d_{\gamma_i} \leq 4A_4 2^{-j}$  and  $E_{\gamma_i} \subset B(\xi, \frac{3}{2}A_4 2^{-j}) \cap D$ , where  $d_{\gamma_i} = 4 \max_{z \in \gamma_i} \delta_D(z)$ ,  $E_{\gamma_i} = \cup_{z \in \gamma_i} \sigma B(z)$  as in Lemma 5.4 and  $A_4 = 2A_1 + 1$ . Further, we see that  $\delta_D(x) \geq c^{-1}d(\xi, x) \geq c^{-1}2^{-j-1}$  and

$$\delta_D(y_j) \geq A_3 \ell(\gamma_\xi(\xi, y_j)) \geq A_3 d(\xi, y_j) \geq A_3 2^{-j-1}$$

by Lemma 5.3. Hence, we obtain by Lemma 5.4

$$\begin{aligned} & |u(x) - u(y_j)| \\ & \leq |u(x) - u(y)| + |u(y_j) - u(y)| \\ & \leq C\kappa_0(\psi(\delta_D(x)), d_{\gamma_1}) \left( \frac{2^{-jQ}}{\mu(B(\xi, \frac{3}{2}A_4 2^{-j}))} \int_{E_{\gamma_1}} g(w)^p \omega(\delta_D(w)) d\mu(w) \right)^{1/p} \\ & \quad + C\kappa_0(\psi(\delta_D(y_j)), d_{\gamma_2}) \left( \frac{2^{-jQ}}{\mu(B(\xi, \frac{3}{2}A_4 2^{-j}))} \int_{E_{\gamma_2}} g(w)^p \omega(\delta_D(w)) d\mu(w) \right)^{1/p} \\ & \leq C\kappa_0(A_5 2^{-j-1}, 4A_4 2^{-j}) \left( \frac{2^{-jQ}}{\mu(B(\xi, \frac{3}{2}A_4 2^{-j}))} \int_{B(\xi, \frac{3}{2}A_4 2^{-j}) \cap D} g(w)^p \omega(\delta_D(w)) d\mu(w) \right)^{1/p} \\ & \leq C 2^{-j} \omega(2^{-j})^{-1/p} \left( \frac{1}{\mu(B(\xi, \frac{3}{2}A_4 2^{-j}))} \int_{B(\xi, \frac{3}{2}A_4 2^{-j}) \cap D} g(w)^p \omega(\delta_D(w)) d\mu(w) \right)^{1/p}, \end{aligned}$$

where  $A_5 = \psi(\min\{c^{-1}, A_3\})$ . Since  $\xi \notin \tilde{E}$  and  $\lim_{j \rightarrow \infty} u(y_j) = L$ ,  $u$  has a nontangential limit  $L$  at  $\xi$ .  $\square$

Proof of Theorem 5.1. For  $r > 0$  sufficiently small, take  $x_1(r) \in \gamma \cap \partial B(\xi, r)$  and  $x_2(r) \in \gamma_\xi \cap \partial B(\xi, r)$ . Then  $x_1(r)$  and  $x_2(r)$  can be connected by a rectifiable curve  $\gamma_0$  in  $D$  with (5.1) and (5.2). Take  $y(r) \in \gamma_0$  such that  $\ell(\gamma_0(x_1(r), y(r))) = \ell(\gamma_0(x_2(r), y(r)))$ , and set  $\gamma_1 = \gamma_0(x_1(r), y(r))$  and  $\gamma_2 = \gamma_0(x_2(r), y(r))$ . Then  $\gamma_1$  and  $\gamma_2$  satisfy (2.4) and (2.5) with  $\eta(t) = A_2 t$  and  $\psi(t) = \min\{A_2, 1\}t/2$ . We see from (5.5) that  $d_{\gamma_i} \leq 4A_4 r$  and  $E_{\gamma_i} \subset B(\xi, \frac{3}{2}A_4 r) \cap D$  for  $i = 1, 2$ . By Lemma 5.4 replacing  $\omega(t)$  with  $\omega(t)t^{-\tau}$ , we have

$$\begin{aligned} (5.6) \quad & |u(x_1(r)) - u(x_2(r))| \\ & \leq |u(x_1(r)) - u(y(r))| + |u(x_2(r)) - u(y(r))| \\ & \leq C\kappa_\tau(0, d_{\gamma_1}) \left( \frac{r^Q}{\mu(B(\xi, \frac{3}{2}A_4 r))} \int_{E_{\gamma_1}} g(w)^p \omega(\delta_D(w)) \delta_D(w)^{-\tau} d\mu(w) \right)^{\frac{1}{p}} \\ & \quad + C\kappa_\tau(0, d_{\gamma_2}) \left( \frac{r^Q}{\mu(B(\xi, \frac{3}{2}A_4 r))} \int_{E_{\gamma_2}} g(w)^p \omega(\delta_D(w)) \delta_D(w)^{-\tau} d\mu(w) \right)^{\frac{1}{p}}. \end{aligned}$$

Take  $z \in \gamma_i$  and  $w \in \sigma B(z)$ . Then note that

$$(5.7) \quad |r - d(\xi, w)| \leq d(x_i(r), w) \leq d(x_i(r), z) + d(z, w) \leq \frac{2 + A_2}{A_2} \delta_D(w),$$

since we have  $d(x_i(r), z) \leq \ell(\gamma_i(x_i(r), z)) \leq A_2^{-1} \delta_D(z)$  by (5.2) and  $\delta_D(z) \leq 2\delta_D(w)$ . Hence we have

$$\begin{aligned} & |u(x_1(r)) - u(x_2(r))|^p \\ & \leq C \kappa_\tau(0, 4A_4 r)^p r^Q \mu(B(\xi, \frac{3}{2}A_4 r))^{-1} \int_{B(\xi, \frac{3}{2}A_4 r) \cap D} g(w)^p \omega(\delta_D(w)) |r - d(\xi, w)|^{-\tau} d\mu(w). \end{aligned}$$

Moreover, since  $0 < \tau < 1$ , we see that

$$\int_{2^{-j-1}}^{2^{-j}} |r - d(\xi, w)|^{-\tau} dr \leq C 2^{-j(1-\tau)}.$$

Hence it follows that

$$\begin{aligned} & \inf_{2^{-j-1} \leq r \leq 2^{-j}} |u(x_1(r)) - u(x_2(r))|^p \\ & \leq C \int_{2^{-j-1}}^{2^{-j}} \left( \kappa_\tau(0, 4A_4 r)^p r^Q \mu(B(\xi, \frac{3}{2}A_4 r))^{-1} \right. \\ & \quad \left. \times \int_{B(\xi, \frac{3}{2}A_4 r) \cap D} g(w)^p \omega(\delta_D(w)) |r - d(\xi, w)|^{-\tau} d\mu(w) \right) \frac{dr}{r} \\ & \leq C \kappa_\tau(0, 4A_4 2^{-j})^p 2^{-j(Q-1)} \mu(B(\xi, \frac{3}{2}A_4 2^{-j}))^{-1} \\ & \quad \times \int_{B(\xi, \frac{3}{2}A_4 2^{-j}) \cap D} g(w)^p \omega(\delta_D(w)) \left( \int_{2^{-j-1}}^{2^{-j}} |r - d(\xi, w)|^{-\tau} dr \right) d\mu(w) \\ & \leq C 2^{-j(Q-\tau)} \kappa_\tau(0, 4A_4 2^{-j})^p \mu(B(\xi, \frac{3}{2}A_4 2^{-j}))^{-1} \int_{B(\xi, \frac{3}{2}A_4 2^{-j}) \cap D} g(w)^p \omega(\delta_D(w)) d\mu(w). \end{aligned}$$

Since  $\xi \notin E$ , we can find a sequence  $\{r_j\}$  such that  $2^{-j-1} \leq r_j \leq 2^{-j}$  and

$$\lim_{j \rightarrow \infty} |u(x_1(r_j)) - u(x_2(r_j))|^p = 0.$$

Since  $u$  has a finite limit  $L$  at  $\xi$  along  $\gamma$ , we have

$$\lim_{j \rightarrow \infty} u(x_2(r_j)) = \lim_{j \rightarrow \infty} u(x_1(r_j)) = L.$$

Thus  $u$  has a nontangential limit  $L$  at  $\xi$  by Lemma 5.5. □

**ACKNOWLEDGEMENTS.** We would like to express our thanks to the referee for his/her kind comments and helpful suggestions.

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